Single-Polarization Fiber Laser Composed of a Normal Single-Mode Erbium-Doped Fiber

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Abstract

We propose a novel single-polarization CW fiber laser composed of a normal single-mode erbium-doped fiber. It features stable single-polarization operation and is free from the spatial hole burning. Its stable operation is demonstrated experimentally.

1. Introduction

The fiber lasers composed of an erbium-doped fiber (EDF), both Fabry-Perot and ring cavity type, have attracted researchers' attention as widely tunable continuous-wave (CW) lasers and mode-locked ultra-short pulse sources, because the EDF has wide gain bandwidth over 50nm at 1.5μm region. The EDF has the gain independent of the state of polarization (SOP) of the signal light, therefore the EDF laser lases at two eigen-state of polarization (ESOP), which are the eigenvectors of the round-trip Jones matrix determined by the birefringence of the fiber[1]. It is, however, not desirable for most of its applications.

To realize the single-polarization fiber laser, a polarization selective element such as a polarizer must be inserted in the cavity. When a normal single-mode EDF (SM-EDF) are used, the SOP in the cavity changes due to the thermal or mechanical perturbation, causing fluctuation of the output optical power and/or lasing wavelength[2]. Therefore, almost all of the single-polarization fiber lasers are composed of polarization maintaining fiber (PMF) components and polarization maintaining EDF, which are still special and expensive. The exception is the Fabry-Perot type CW fiber laser using an SM-EDF, a Faraday rotator mirror (FRM) and a polarization beam splitter (PBS)[3]. However, it is a little complicated and not free from the spatial hole burning caused by the standing wave in the Fabry-Perot cavity.

In this paper, we propose a novel single-polarization CW fiber laser composed of a normal SM-EDF. It features stable single-polarization operation and is free from the spatial hole burning. We demonstrate its stable operation in the output power and the lasing wavelength in a experiment.

2. Construction and Principle of Operation

The proposed fiber laser is composed of two FRMs forming a Fabry-Perot cavity and a normal SM-EDF between them, as shown in Fig.1. One of the FRMs is a normal one, and the other is a special one in which a polarizer is inserted between the mirror and the 45° Faraday rotator (FR). The mirror has reflectivity of (100-α)% to output α% of the intra-cavity light. The SM-EDF is pumped by a laser diode (LD) of 1.48μm or 0.98μm through a wavelength division multiplexing (WDM) coupler, and a bandpass filter (BPF) is inserted to tune the lasing wavelength.

When we consider the SOPs of the forward (rightward) and the backward (leftward) light beams at a point A (between the FR1 and BPF) in Fig.1, the backward SOP is stabilized to be orthogonal to the forward SOP even if the birefringence changes[4][5]. Here we describe the SOP behavior in the laser using the Jones matrix[6]. We adopt the coordinate system moving with the light beam.

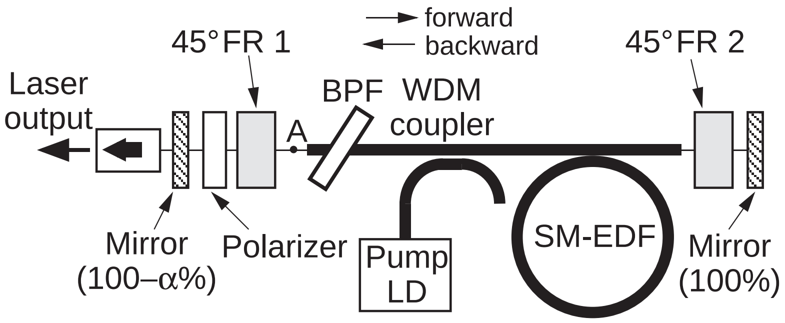

Fig. 1: Proposed single-polarization fiber laser composed of a normal SM-EDF

The Jones matrix of a mirror $\boldsymbol{T}_M = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$, that of a 45° FR in the forward direction $\boldsymbol{R}_{FR,f} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$, and in the backward direction $\boldsymbol{R}_{FR,b} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$, therefore the Jones matrix of the FRM is expressed as

$$\boldsymbol{T}_{FRM} = \boldsymbol{R}_{FR,b} \boldsymbol{T}_M \boldsymbol{R}_{FR,f} = t \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} . \tag{1}$$

where t is the loss in the FRM. The Jones matrices of the SM-EDF in the forward direction is $\boldsymbol{R}_{SM,f} = \frac{g}{d} \begin{pmatrix} a & -b^* \\ b & a^* \end{pmatrix}$, and the backward direction $\boldsymbol{R}_{SM,b} = \frac{g}{d} \begin{pmatrix} a & -b \\ b^* & a^* \end{pmatrix}$, where * denotes the conjugate, g is the EDF gain including the loss of the components, a and b represent the birefringence in the SM-EDF which varies due to the external perturbation, $d^2 = a \cdot a^* + b \cdot b^*$. Therefore the Jones matrix of the part of the FRM and the SM-EDF $\boldsymbol{S}$ is

$$\boldsymbol{S} = \boldsymbol{R}_{SM,b} \boldsymbol{T}_{FRM} \boldsymbol{R}_{SM,f} = tg^2 \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix} . \tag{2}$$

It is found that the backward SOP is stabilized to be orthogonal to the forward SOP regardless of the change of a and b. It should be noted that the polarization mode dispersion (PMD) in the SM-EDF, which causes the change of the lasing wavelength of the fiber laser with a polarizer[2], is thoroughly compensated[6]. And the polarization dependent gain or loss is averaged therefore also compensated.

The output of the polarizer in a linear SOP in the forward direction is rotated by +45° by the FR1, goes into the part of an SM-EDF and an FRM, reflected back with −90° rotation, and again rotated by +45° by the FR1, thus the SOP of returned light is identical to initial linear SOP. It can also described as follows. The Jones matrix of a polarizer is $\boldsymbol{R}_{POL} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, therefore the Jones matrix of a round trip in the cavity $\boldsymbol{U}$ becomes

$$\boldsymbol{U} = \boldsymbol{R}_{POL} \boldsymbol{R}_{FR,b} \boldsymbol{R}_{SM,b} \boldsymbol{T}_{FRM} \boldsymbol{R}_{SM,f} \boldsymbol{R}_{FR,f} \boldsymbol{R}_{POL} \boldsymbol{T}_M = tg^2 \begin{pmatrix} -1 & 0 \\ 0 & 0 \end{pmatrix} . \tag{3}$$

It means that only one linear SOP in a constant power can lase even with external perturbations.

It can be proved that the laser does not have standing wave in the SM-EDF as follows. If we denote the Jones vector at a point in the forward direction $(E_x, E_y)^t$, that in the backward direction becomes $(-E_y, -E_x)^t$ using Eq.(2). Here we fix the coordinate to the forward direction to represent the standing wave, then the Jones vector in the backward direction, considering the reversal of the phase, becomes $(E_y^*, -E_x^*)^t$. Therefore, the electric field vector in the forward and the backward directions are $\vec{E_f} = (E_x, E_y)^t e^{j(\omega t - \beta z)}$ and $\vec{E_b} = (E_y^*, -E_x^*)^t e^{j(\omega t + \beta z)}$, and the field intensity becomes $|\vec{E_f} + \vec{E_b}|^2 = 2|E_x|^2 + 2|E_y|^2$, thus there exists no standing wave in the SM-EDF. The standing wave is

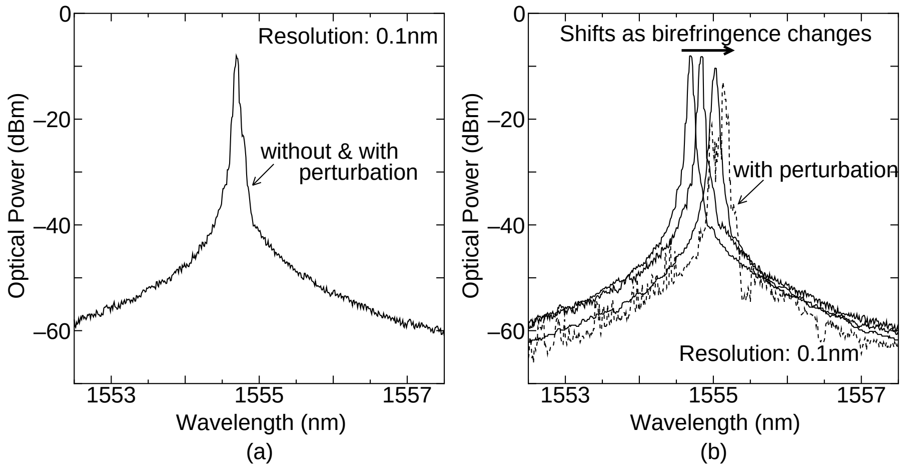

Fig. 2: Output optical spectra in cases using (a) an FRM, and (b) a normal mirror

considered to be main cause of the multimode oscillation[7], therefore the proposed laser is expected to lase stably at a single mode.

3. Experiment

To confirm the stable operation in the output power and the lasing wavelength of the proposed laser, we performed an experiment. The SM-EDF is about 40m long, has the Er-concentration of about 1000ppm, and pumped by a 1.48μm LD of 20-30mW through a WDM coupler. The BPF of 1nm is used to tune the lasing wavelength. One end of the cavity is a commercially available FRM, and another end consists of a 95% mirror, a 45° FR and a polarizer. One of polarizers in a normal polarization dependent isolator is removed and used as the 45° FR and the polarizer. The laser output from 95% mirror is fed into a normal polarization dependent isolator to prevent the reflection. Total cavity length is about 50m, and the corresponding longitudinal mode spacing is 2MHz.

Figure 2(a) shows the obtained optical spectra of the proposed fiber laser. A single-mode spectrum is obtained at the resolution of 0.1nm, and the lasing wavelength coincides with the center wavelength of the BPF. The spectrum hardly changes even when the stress or the mechanical perturbation is imposed on the cavity. Figure 2(b) shows the spectra in the case where a normal mirror is used instead of an FRM (FR2 is removed in Fig.1). In this case, the lasing wavelength shifts as the birefringence changes by imposing the stress on the cavity[2]. When the fast mechanical perturbation is imposed, the spectrum is destroyed (dotted line).

Figure 3 shows the relations among the center wavelength of the BPF, the lasing wavelength, and the output power. The lasing wavelength is found to coincide with the center wavelength of the BPF. The relatively low output power (about -9dBm) and narrow tuning range (about 25nm) is because too long EDF is used; we expect the use of a length optimized EDF enhance them.

As far as the observation of the optical spectrum at the resolution of 0.1nm (Fig.2(a)), the laser operates at a single mode. To examine the spectrum with much higher resolution, we observed the beat between the laser output and the light from an external cavity LD which operate at a single mode and whose linewidth is less than 100kHz. A balanced coherent receiver is used to remove the direct-detection components. Figure 4 shows the observed microwave beat spectra. Without external perturbation, the spectrum becomes sometimes single-mode as shown in Fig.4(a). However, it is not stable, but lasts at most 1 second. In most of cases, it is in the mode-competed state or in the unstable multimode state as shown in Fig.4(b). The erbium is considered to be homogeneous within the bandwidth of 1nm, and this laser has no standing wave, therefore we expect it should operate at a single mode. We attribute the unstable single-mode operation to the reflection at the connection points

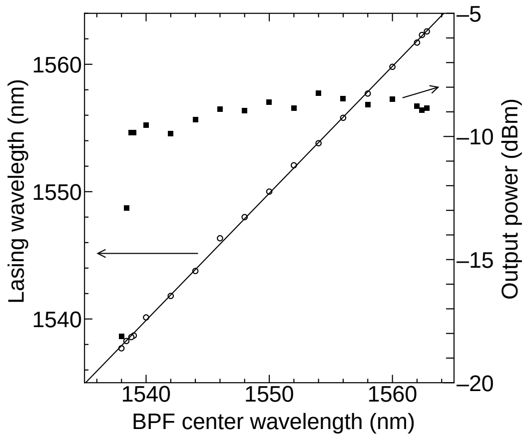

Fig. 3: Relations among the BPF center wavelength, the lasing wavelength, and the output power

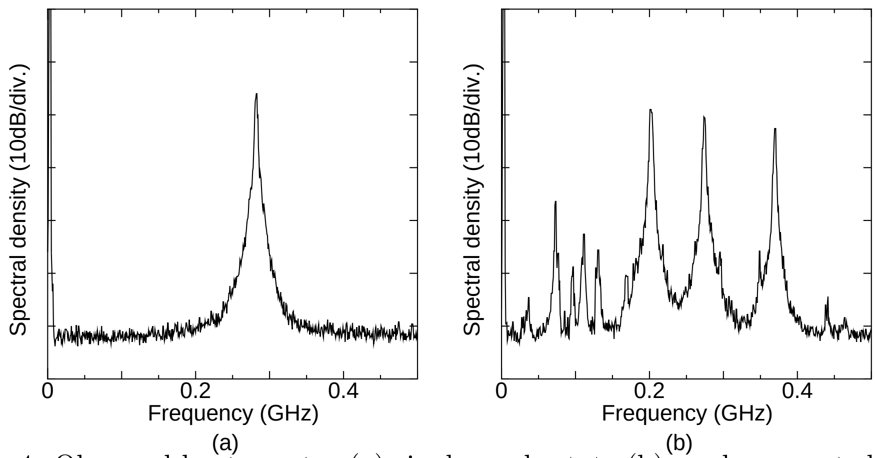

Fig. 4: Observed beat spectra (a) single-mode state (b) mode-competed state

within the cavity (FC connector is used at present) and the remaining mechanical perturbations. We are now planning to construct the laser connected by splicing and stabilized in a sealed box.

4. Conclusion

We have proposed a novel single-polarization CW fiber laser composed of a normal SM-EDF. It features stable single-polarization operation and is free from the spatial hole burning. We have demonstrated its stable operation in the output power and the lasing wavelength in a experiment. The laser is expected to operate at a single mode, whereas it operated at an unstable and mode-competed single mode.

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